TITLE: Non-Auditory Damage Risk Assessment for Impulse Noise

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Non-Auditory Damage Risk Assessment for Impulse Noise

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Abstract This paper discusses the non-injury thresholds established for three different complex waveforms. These animal studies were accomplished by EG&G at the Blast overpressure Test Site at Kirtland AFB in New Mexico. Human volunteer studies were also performed. The human studies verified non-injury levels for three different freefield waveforms and one complex waveform. The use of the Bowen model developed nearly 40 years earlier, as well as two later models, will be discussed. A simple relationship between an "acceptability limit" and the non-auditory injury limit was found to exist. This "acceptability limit" was found to be approximately 70 % to 80% of the non-injury limit in peak pressure in kPa. This small reduction in peak level provides a sufficient safety factor for all possible waveforms, both complex and freefield, and a simple mathematical equation is recommended as a practical design goal.

Introduction Criteria for non-auditory injury for freefield impulse noise has been available since the late 60's (Richman, et. al., 1966 and Bowen, et. al., 1968). Gas containing organs were found to be much more vulnerable to direct blast than solid organs. Using this knowledge, Bowen established criteria using an early model based on the response of the lungs to a simple Friedlander wave. Criteria for complex impulsive waveforms, however, have been virtually non-existent until recently. Over the last ten years there has been some significant changes. Two new computer based models have been proposed. (Axelssen and Yelverton, 1996 and Stuhmiller, et. al., 1996) In addition, animal experimentation has demonstrated the non-injury threshold levels for three different complex waveforms.(Yelverton, et al, 1993,Yelverton, et al, 1997, Yelverton, et al, 1997, Merickel, et al, 1997) A human study, using 60 subjects, has verified these limits for one of these three complex waveforms.(Johnson, 1998) Human studies have also verified a non-injury level for three different freefield exposure conditions consisting of both 6 and 100 exposures spaced at one-minute intervals.(Johnson, 1994 and Johnson 1998) Over 120 subjects were used for the waveform that was like a large howitzer. About sixty subjects were used for each of the waveforms that were more like mortar fire. These results serve as very strong anchor points for any non-auditory risk criteria. It would have been useful for human studies to have backed up the animal results for all three complex waveforms, but budget cuts prevented this from happening. However, the results of the animal studies have so far been a good predictor of the human results. This encouraging result suggests that some simple criteria using some "worst case waveforms" can be proposed for complex waveforms in general. These criteria will err on the safe side. In the cases that this is not acceptable, use of one of the computer models is suggested.

Freefield waveform criteria

The Bowen Model: Numerous mammalian mortality studies have demonstrated that tolerance to classical blast waves is dependent upon the peak overpressure, the overpressure positive phase duration and the animal species. (Richman, et al, 1968,Bowen, et al, 1968). Review of mortality data shows three concepts: 1. The data separates into "small" and "large' mammal groups; 2. There is a linear relationship between the probability of mortality and the logarithm of peak pressure and 3. The lines have a common slope, suggesting a common mechanism of lethality. For these reasons, it is not surprising that sheep should serve as a good model for determining the effects of blast on humans. Unfortunately, because being based on lethality data, the Bowen model is more accurate at the 50% lethality point than at the "threshold of injury point." However, the Bowen curves have been extended down to include threshold of injury. Thus the shape of the curve with respect to peak pressure versus duration remains the same. There is some early animal data that support the Bowen reflective threshold limit curve as shown in figure one, but the best support for the general shape of this curve comes from recent human data.

Recent Human Exposures Because the U.S. Army was concerned about non-auditory injury from training with large weapons, the Army began to use the Z-curve plotted in figure 1.. This curve was considered a conservative non-auditory limit as well as a limit for hearing conservation while wearing hearing protection. This Z-curve is based on auditory data from small arms fire and was developed by U.S. National Research Council Committee as criterion for preventing hearing loss from impulse noise. (CHABA, 1968). Because the Z-curve was considered likely to be very over-protective with respect to non-auditory risk, some studies designed to be at the expected non-auditory

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limits for several weapon systems were funded by the U. S. Army. These were started in 1989 and completed in 1997.

The results of the human studies are plotted in figure 1. The human studies come from the final reports of the blast overpressure studies recently finished at Kirtland AFB for the U. S. Army. (Johnson, 1993, Johnson, 1997) At the highest peak pressures, which occurred six times at I minute intervals, with but two exceptions, no non-auditory injury was observed. There were 104 subjects for the 190 dB, 3-ms duration exposures; 67 subjects for the 193 dB, 1.4-ms duration exposure; and 52 subjects for the 196 dB, 0.8-ms duration exposure. One of the two exceptions was a hematoma on the eardrum of one subject whose ear was only protected by a leaking muff. The other exception was a subject that had bruised his ribs by playing football. He complained that the blast caused great discomfort to his ribs and eventually he elected to drop from the study. These exposures all fall below the Bowen reflective limit curve of figure 1. The shape of the reflective limit curve, at least for these conditions, seems to be reasonable.

Complex waveform criteria The response of mammals to complex waveforms has been difficult to interpret. Peak pressure and duration of the positive pulse are not sufficient descriptors of the waveform. The rate of rise, the amount of the negative phase, the location of the maximum peak in time, and the frequency of oscillation may be additional parameters of importance. For example, the protective effects of "long-duration" pressure loading has been demonstrated by pressurizing animals to increasingly larger ambient pressure levels prior to blast exposure (Damon, et al, 1966). It was found that resistance to blast injury increased as the ambient pressure increased. To resolve some of the difficulty, animal experimentation undertaken to determine the non-injury limits for several types of typical complex waveforms.

Recent Animal Exposures The recent animal exposures have consisted of three different types of waveforms. The first wave form is of the type typical of shooting a recoilless rifle out of a bunker. As shown if figure 2, this waveform is characterized by a very long duration of highly oscillating pressure. The second waveform used is one characteristic of an enclosed space that is open to the pressure wave of a large muzzle blast. This could occur in a self-propelled howitzer with its doors open. As shown in figure 2, this waveform has a rather slow rise time as well as a long and significant negative pressure phase. The third waveform used is one characteristic of firing a mortar out of a partially enclosed space such as an armored personnel carrier. This waveform has a small precursor wave followed by a more classical freefield wave, then a significant negative wave.

1) Firing from bunker results. An early study in 1976 using rabbits suggested a significant risk of non-auditory injury from firing the Carl-Gustaf recoilless rifle. Using two or three shots at 1 minute intervals, nearly 35% of the rabbits sustained moderate to severe injuries from peak pressures not exceeding 186 dB (40kPa). The spectral analysis of the waveform showed the strongest pressure components to be in the 150-500 Hz range. This range matches the natural frequency of the rabbit, (von Gierke, 1968), thereby enhancing injury (Clemedson and Jonsson, 1976). At Kirtland AFB in the early 1990's, a 17.3 cubic meter chamber was built to serve as the bunker. Explosive charges were detonated outside of the bunker and some of the resulting blast was funneled into the bunker through a pipe 249 cm. in length and 20.3 cm in internal diameter. The typical resulting blast wave inside the chamber is shown in figure 2a. In a study using sheep that was completed in 1993, the proven sub-threshold of injury level was shown to be 48 kPa for one shot, 44 kPa for 3 shots. (Yelverton, et al, 1993) In 1997,19 sheep were used to verify a sub-threshold level of 23 kPa for 100 shots (Merickel, et al, 1997).

2) Self propelled howitzer muzzle blast results (Yelverton, et al, 1997): At the Army blast pressure test site, the hull of an M108 Self propelled howitzer with the back door open was used as the crew compartment. The muzzle blast was simulated exploding C-4 inside a large tube and directing the resulting blast waves over the M108 hull. A reflector was used to reflect some of the blast into the hull. See figure 2b for the resulting simulation. Sheep were exposed to the blasts at one-minute intervals. One subject was supported vertically in the gunner position and one subject was supported vertically in the loader position. Twenty-two controls were used during the study. Using 30 sheep, it was found that the sub-threshold of injury was 27 kPa for 6 blasts. Using 10 sheep for the 25 blast sequences and 40 sheep for the 100 blast sequences, it was found 20 kPa was the sub-threshold level for both sequences. Unacceptable number of lesions to the pharynx/larynx occurred when the overpressure was 32 kPa for 6 blasts (6 lesions out of 10 animals) and 24 kPa for 25 blasts (3/10).

3) 120mm mortar blasts from an enclosed space results (Yelverton, et al, 1997): At the Army Blast over pressure Test Site, a vertical explosively driven shock tube, in combination with reflector plates, was used to simulate the waveform of the 121mm mortar shot out of an Armored Personnel Carrier. The resulting waveform is shown in figure 2c. Using C-4 as the explosive charge, the blasts were set off in one-minute increments. The results of the study demonstrated sub-threshold injury level as 36 kPa for 6 shots each and as 30 kPa for 50 shots each.

Recent Human Exposures

Firing from the bunker results: After the sub-threshold levels were established by exposing anesthetized sheep, a walkup study at the Army Blast Overpressure Site using 64 army volunteers was started in 1994 (Johnson, 1997). The same bunker simulation was used. Because of the need to start the exposures at very low levels so that the subjects could become acclimated to the blasts, the first level was at a peak of about 6 kPa. for one shot. The levels were increased in 7 steps to 48 kPa. If a subject passed that level, the next exposure was two shots at 44 kPa. The final exposure was 3 blasts at 44 kPa. Fifty-nine subjects passed through the entire exposure sequence without any known problem with respect to non-auditory problems. Three subjects elected to quit and two subjects were dropped for administrative reasons. Daily medical exams, including hemoguaiac testing, verified the lack of any injury. For these reasons, the sheep did serve as a conservative model for predicting safe, non-auditory exposures in humans.

The models There are two published approaches for modeling the human response to complex waveforms. These are a model proposed by Axelsson and Yelverton based upon maximum chest velocity (Axelsson and Yelverton, 1996) and a model proposed by The Walter Reed Army Institute of Research/ JAYCOR based on work (Stuhmiller *et. al.*, 1999).

Neither or these models are commercially available and have not been standardized. Until this occurs, neither one of these promising models will fill the needs of the design community.

1) The chest velocity model: Axelsson and Yelverton took a single degree of freedom model, originally developed to measure the response of the thorax to simple Friedlander waves, to calculate chest wall velocities resulting from complex waveforms such as shown in figure 2 (Axelsson and Yelverton, 1996). The results found with sheep demonstrated a good relationship between the overall Injury Index (which included the lungs, upper respiratory tract, gastrointestinal tract and solid intra-abdominal organs) and the calculated maximum inward chest velocity. They also found a good correlation between chest wall velocity and the established Friedlander prediction curves of the Bowen model. The velocity of complex blast waves was nearly the same as that of Friedlander wave for a given degree of injury. These velocities were found to be 3 to 4.5 meters/second for the threshold of injury, 8 to 12 meters/second for 1-% lethality, and 12 to 17 meters/second for 50% lethality. (Axelsson and Yelverton, 1996)

2) The Walter Reed Army Institute of Research/ JAYCOR BLAST INJURY model: (Stuhmiller *et. al.*, 1999) For more than ten years the U.S. Army has funded an effort by JAYCOR to develop a lung injury model. The mathematical model of the chest wall dynamics, and the resulting pressure waves in the lung, is used to predict injury. (Stuhmiller *et al.*, 1996) The model has been compared, and I assume adjusted, to the relative large number of animal data from the Army's Blast Over-pressure studies as well as other studies. One of the bases of the model is the observation that the incidence of injury follows a log normal correlation with the computed total energy in these waves. Thus this relative simple model allows lung injury be predicted from measured or predicted pressure traces. (Stuhmiller *et al.*, 1996) It is worthy to note that the sub-threshold of injury freefield overpressure levels that were used to establish the upper levels for 6 shot and 100 shot sequences for the human exposures came from an earlier version of this model. According to JAYCOR, the model is being evaluated by a third party review and has not been formally released. This is a step that must be done. Also, this model only predicts lung injury, using the assumption that lung injury is the precursor to any other type of injury.

Possible Criteria for both Complex waves and Friedlander waves In figure 3 the data from the various animal and human studies are plotted on a common graph. The Bowen threshold curve is also plotted. They are quite consistent with each other. In fact, I believe that a simplified model can be derived from the data plotted in this figure. One of the keys of doing this is the observation that the various complex waveforms serve as a set of worse case examples and that most complex waveform will be a less injurious subset of these waveforms given that the peak pressure is the same. This will be discussed further in the following paragraph. One of the factors that is not discussed is the acceptability of a human to expose himself or herself right at the threshold of injury. For many of the human volunteers, there was a definite reluctance to expose themselves at the very top level. The exposure ceased to "be fun". My belief that there will be a greater chance a weapon will be used properly if it is not scary to use. For this reason, the criteria will be reduced slightly. This reduction also builds in a slight safety margin in case are assumption that we have used worst case waveforms is not quite true.

Worse case waveforms Figure 2 shows three waveforms that were selected to be typical of different types of complex blast waves. What is not shown is the effort by the investigators, in this case John Yelverton and myself, to make these as dangerous as possible. For example, the bunker, in which the firing from the bunker simulation was made, was designed to resonant at the frequencies from 50 – 60 Hz. These are the natural frequencies of the chest and for that reason are expected to be the most dangerous. For the Self-propelled howitzer, a considerable effort was expended to produce the long negative pressure that followed the initial positive part of the wave. The idea was to make the lung expand more quickly after the initial compression. My contention is the most complex waveforms will be less dangerous that the ones used in figure 2. A perfect application of the mathematical models described above is to challenge this contention.

Human Acceptability At the end of a subject's exposure to a specific waveform at all the different number and levels of blasts, the subject was given two sets of questionnaires related to acceptability. One set of questions simply asked if he would find it acceptable to train at the various exposures that he received. The other questionnaire asks the subject to mark one of the 5 statements the most closely related to his feelings (Johnson, 1993 and Johnson, 1997). The results of these questions for the three freefield waveforms and the firing from bunker waveform are summarized in table 1. The exposures that were at the threshold of the non-auditory limits were the 6 shot exposure at level 7 and the 100 shot exposure at level 6. There was approximately 3 dB difference between the levels. Note that the dislike of the subjects for the exposures increases quickly when level 7 is reached. Likewise, the dislike increases at level 6 as the number of blasts in increased. Should a weapon designer worry about acceptance? Clearly a certain percentage of the subjects did accept the exposures. In fact, there were a few subjects that were disappointed in that there were not higher exposure levels available, especially for the 6 blast sequence. I know that I would have been exposed to a higher level in the firing from the bunker simulation. Having been exposed to several shots at all the waveforms, I felt that the bunker simulation was the weakest of the lot with respect to physical discomfort. The subject generally stated that the number of exposures became a problem past 25 blasts per day. This can be seen in table 1. The subjects were given a count down so that they could be prepared when the blast occurred. Without this count down, the acceptance of these exposures would certainly be lower.

Table 1. Percent of the subjects that rated the stated exposure as unacceptable with respect to training. There is about a 3 decibel difference between levels.

	Level 7	Level 6	Level 5	Level 4
Bunker 1 shot	20*	12	3	1
1 meter 6 shot	40*	3	0	0
3 meter 6 shot	37*	0	0	0
5 meter 6 shot	36*	0	0	0
Bunker 3 shot		25*	8	1
1 meter 100 shot		69*	32	14
3 meter 100 shot		48*	33	10
5 meter 100 shot		57*	26	11

- ****Non-auditory sub-threshold of injury***

Recommended design criteria The design criteria that I recommend is as follows:

For free field waves with a clearly defined A-duration under 10 ms

Max peak = 195 dB – 10 log (A-Duration) –2.5 log (N)

And for all other transient waveforms

Max peak = 185 dB-2.5 log (N)

Where: The max peak is an average with a standard deviation of less than 1 dB

The A-duration is the time in milliseconds that the positive going peak overpressure stays positive without going negative.

For non-freefield waveforms, the Max peak is the greatest overpressure observed during the transient.

N is the number of individual transients during any day.

Comments; The proposed criteria should handle any conceivable waveform. In basically ignores the duration of a complex waveform as based on the fact that all of the animal research up to now has shown that the peak overpressure is a better measure of the non-injury level. Nevertheless, these levels are approximately 2 decibels lower than probably the true threshold to account for human acceptability and to provide a small safety factor in case the worst case assumption is not quite true. The long A-duration that in likely from a nuclear explosion is also covered by this criteria due to the fact that 185 dB is the approximated level that the non-injury curse of Bowen asymptotes with respect to duration.

Exceptions The suggested criteria do not handle the case where the blast causes an airflow such as when a blast enters a structure with a door. The resulting displacement of a body is outside the scope of these criteria.

Conclusions Considerable human and animal data now exists with respect to a non-injury threshold for both simple and complex waves. A simple criterion for the sub-threshold for blast injury has been proposed. One of the key concepts for this criterion is to eliminate the concept of duration for complex waveforms. The levels have been dropped slightly to make the exposures more acceptable to the exposed soldiers and to provide a small safety factor. This approach provides a lower bound with respect to the non-auditory threshold for any complex waveform. In order to raise this limit for a complex waveform that might not be as injurious as the waveforms that established the criteria, the use of one of the existing models is suggested. These models are referenced; however, they are not as readily available as they need to be. They need to be standardized and provided as a software program, perhaps one that can be downloaded from a website.

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Figures

Figure 1 The threshold of lung injury from the Bowen model (Yelverton, et al, 1996) as well as the Z-curve used in MIL-STD-1474C. Also plotted are various data from humans, sheep and dogs. The open circles were cases in which no petechiae were observed. The half-filled circles indicate that one-half of the dogs or sheep had some petechiae on the lungs. The solid circles indicate that some small isolated hemorrhages occurred. For the human studies, the lack of lung petechiae is assumed from the lack of petechiae on the larynx-pharynx. The F and R indicate the exposure was freefield or reflective, respectively. Adapted from figure 9 of Yelverton, et al, 1996.

Figure 2

a Pressure time pattern from "Firing anti-tank weapon from the bunker" simulation

b Pressure time pattern from "Firing 155 Self Propelled Howitzer with open doors" simulation

c Pressure time pattern from "Firing 121 mm mortar from Armored Personal Carrier" simulation

Figure 3 The fit of the data to the proposed formula: 195 dB –10 log(T) – 2.5 log(N).

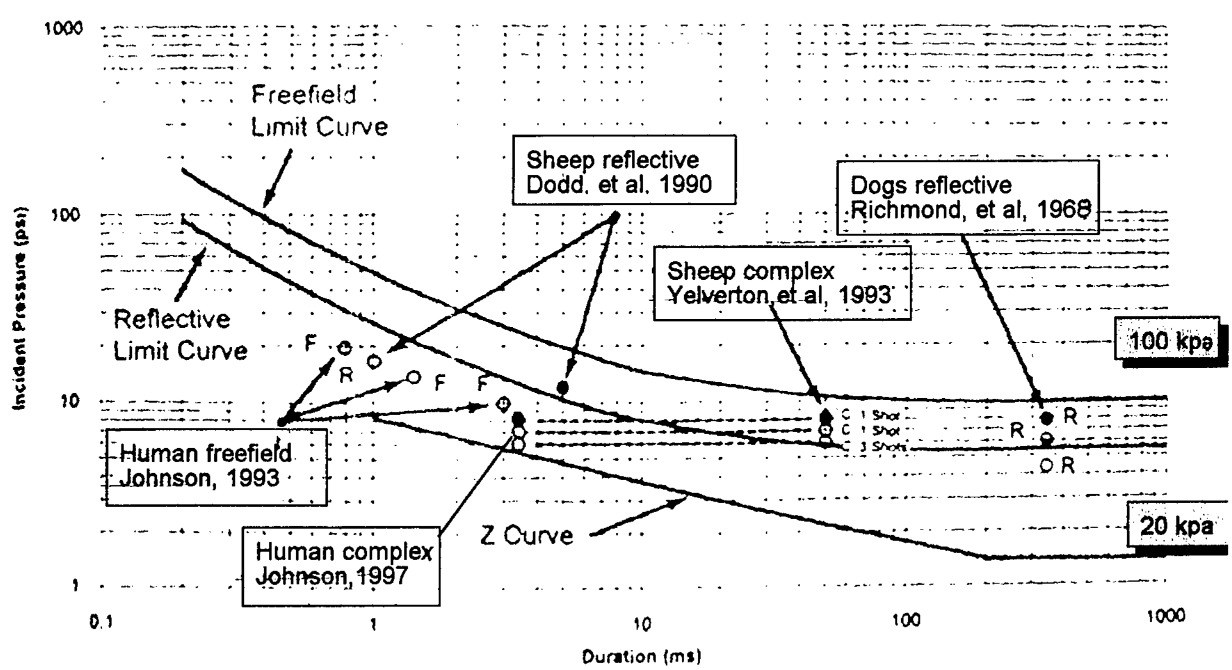


Figure 1

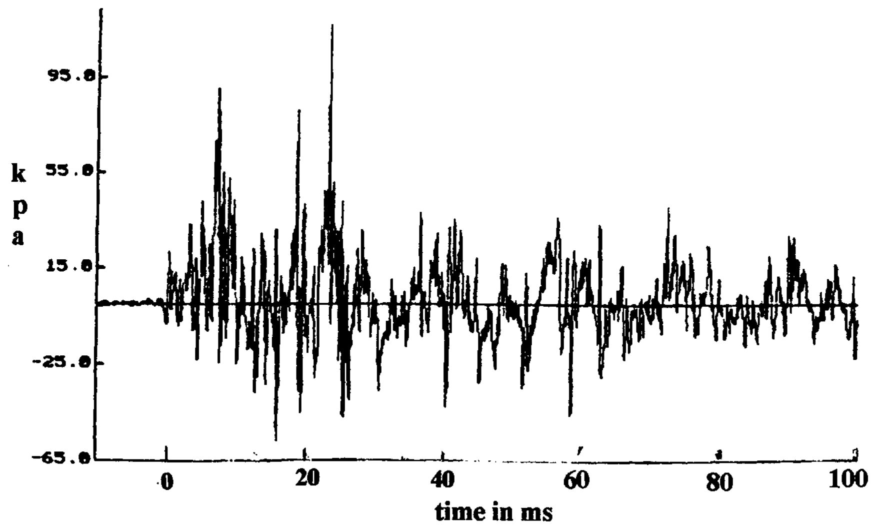


Figure 2a Pressure time pattern from "Firing anti-tank weapon from the bunker" simulation

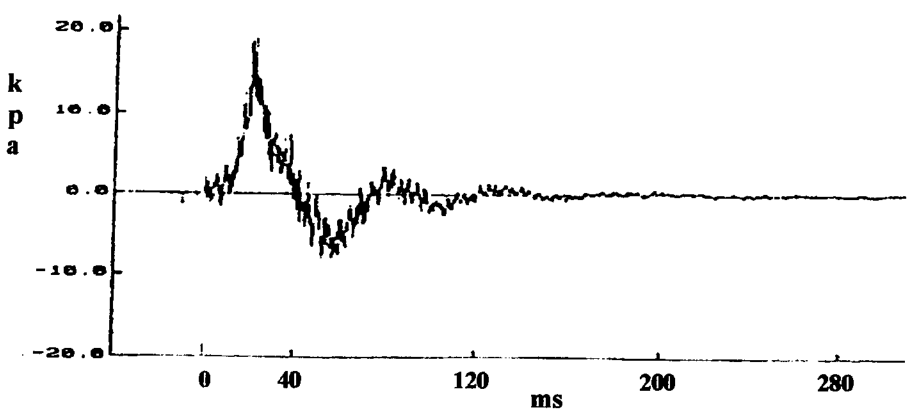


Figure 2b Pressure time pattern from "Firing 155 Self Propelled Howitzer with open doors" simulation

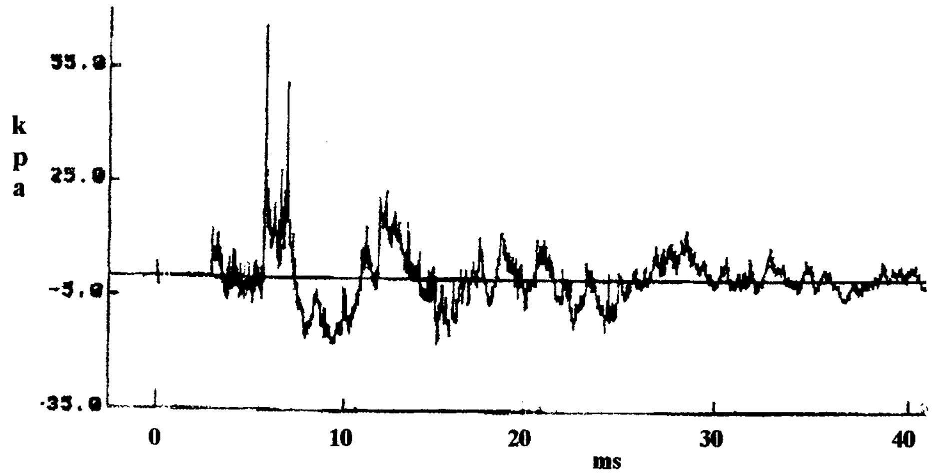
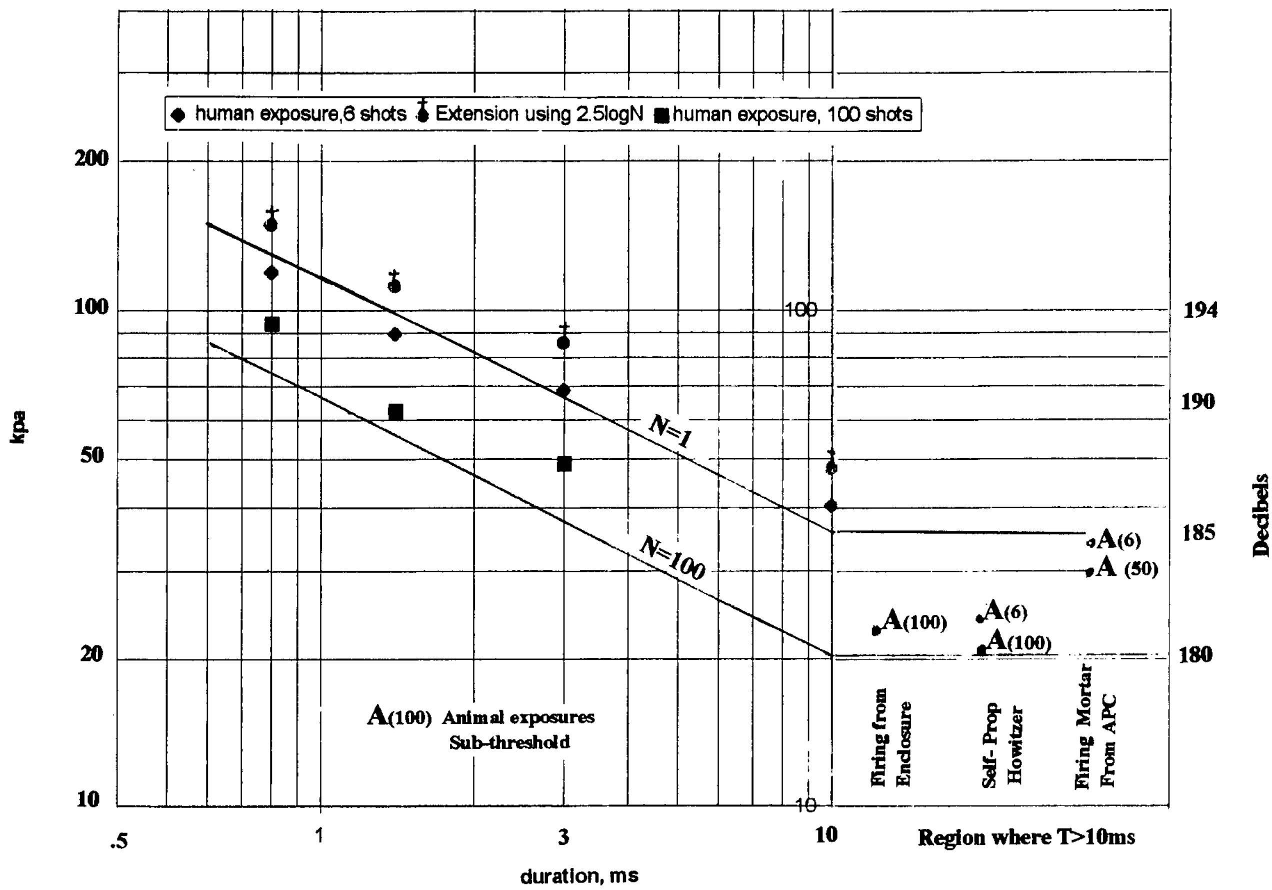


Figure 2c Pressure time pattern from "Firing 121 mm mortar from Armored Personal Carrier" simulation



human exposure,6 shots
Extension using 2.5logN
human exposure, 100 shots
200
100
50
20
10
kpa
N=1
N=100
A(100) Animal exposures
Sub-threshold
A(6)
A (50)
A(100)
A(6)
A(100)
194
190
185
180
Decibels
Firing from Enclosure
Self- Prop Howitzer
Firing Mortar From APC
.5
1
3
10
Region where T>10ms
duration, ms

Figure 3